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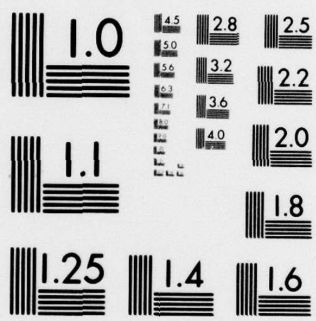

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Superconducting Microwave Pulse Amplifier

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SUPERCONDUCTING MICROWAVE PULSE AMPLIFIER

Final Report

July 1979

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This report summarizes the preliminary research and development of a new and novel technique for very high power microwave pulse amplification. The technique is based on the principle of time compression and is most efficient when utilized in conjunction with superconducting (cryogenic) components. However, it has also been shown to be applicable as a purely ambiant temperature device. Very high power microwave pulses appear to be feasible with this technique.

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INTRODUCTION AND SUMMARY

The main purpose of this report is to discuss the research and development carried out by RAI under ONR Contract #N00014-75-C-1115 during the year ending 30 June 1979. However, the report also presents a background summary of previous work under this contract. Basically the project has demonstrated the viability of a new and novel technique for very high power microwave pulse amplification.

This new method is based on time compression. The basic ideas were first published in a November, 1972 RAI report sponsored by ONR entitled "Naval Applications of Superconducting Devices." Analytic development of the concept, utilizing electromechanical interactions was sponsored by ARPA via ONR and resulted in a June, 1976 RAI report, "Electromechanical Energy Conversion at Microwave Frequency." From that study it became apparent that the most immediate application probably lay in microwave pulse amplification, and that purely electronic techniques were more viable than mechanical methods for this purpose.

Further analytic and experimental research on superconducting microwave pulse amplifiers, sponsored by ONR, resulted in a January, 1978 RAI report entitled, "Superconducting Microwave Energy Compressor." That report outlined some characteristics of such a device and discussed preliminary experiments on a low power demonstration prototype.

The two fundamental features of this new technique are: (1) the accumulation (or "storage") of large amounts of microwave energy from a low power source; and, (2) the subsequent rapid release (or"switch") of this energy into a high power pulse.

In the past year, research has been directed toward developing and demonstrating this technique at higher microwave energy and power. Both superconducting and room temperature storage techniques have been studied and demonstrated experimentally. Energy storage of more than 6 J of S-band microwave energy was achieved, power gain in excess of 10^4 was demonststrated, and a new type of high power electron beam microwave interference switch was developed.

Patent disclosures covering the basic technique and the electron beam switch have been made and patent applications are being processed by ONR. Much of the scientific and technical results discussed later in this report have been published in scientific literature. References to these publications are given in the text.

The basic components which are used in the foregoing technique of pulse generation are an overmoded microwave storage resonator and a microwave interference switch. Both of these components have been developed and studied by RAI in prototype form. The concept and first test of the switch were reported in Appl. Phys. Lett. 32, 68 (1978). An updated report of that research was also given at the September, 1978 Applied Superconductivity Conference as a paper BA-6 and published in IEEE Mag-15, 33(1979). Microwave energy storage in TE mode superconducting resonators was also reported at that Conference as Paper BA-7. Some unique characteristics of microwave pulses formed by this technique (phase coherence and frequency modulation) were reported in Appl. Phys. Lett. 33, 466 (1978) issue.

From the foregoing experimental basis, an extrapolation can be made to estimate the limits of the technique which are set by superconducting material characteristics or microwave technology. RAI, in collaboration

with General Electric-Tempo, has made such an extrapolation which indicated that at S-band frequency and above this technique has the potential to produce microwave pulses at power levels exceeding that from any alternative technology, including the relativistic electron beam devices. The details of this extrapolation are contained in a 1978 GE report to BMDATC, Huntsville. As an example of a relatively small-scale device, a 4 liter volume ($\simeq$4" radius sphere) Nb superconducting resonator can accumulate up to $\sim$10 J energy from a 10 watt X-band source. Switched into a 10nsec pulse results in a peak power of $\sim$1 Gw and power gain of $\sim 10^8$. Further analysis (RAI Report #29819 GE-Tempo) indicates that such devices can be scaled up to $\simeq 10^3$ liter volume where energy $\sim 5 \times 10^3$ J and peak pulse power at X-band $\sim 10^{11}$ W seem feasible. However, it must be emphasized that experimental research thus far has been at relatively low power. Much more research and development must be done to carry the technique to its high power limits.

MICROWAVE ENERGY STORAGE

In order to accumulate large amounts of microwave energy, large resonator volume is necessary. This large volume in turn complicates the electrodynamic characteristics of the resonator by introducing a large number of resonant modes. Consequently, a significant fraction of this research was devoted to analytic and experimental study of overmoded microwave resonators. Techniques were developed to split off unwanted modes and to preferentially couple to the desired mode. Experiments were done at both X- and S-band microwave fequency and with both superconducting and room temperature storage resonators.

The S-band superconducting storage experiments were done with a modestly overmoded, 15 liter volume, TE_{022} cylindrical S-band resonator, fabricated of lead (Pb) plated copper (Cu). Superconductor Pb cannot achieve the very high power gain noted above for Nb because of a somewhat higher surface resistance. However, it was chosen for the initial tests because of ease in fabrication. The low power quality factor (Q_0) of this superconducting resonator was approximately at the BCS theoretical limit; $Q_o \simeq 5 \times 10^9$. Curve A on Figure 1 indicates typical data on energy storage as a function of pump power. Above about 1 J, in this data, the resonator Q drops to $\sim 10^9$ and the stored energy is about 5x less than the BCS limit. This break point is a function of surface preparation of the superconducting material and is the subject of other research. We believe that it is indicative of a local defect in the material which causes a small spot to go normal and dominate the Q. However, it should be noted that there are no "run away" effects - the resonator remains thermally and electrodynamically stable. Further, there is no evidence of field emission or multipacting. Small sample tests of this material indicate that it remains superconducting up to rf fields $\simeq$ 800 gauss. Consequently we feel that, with more careful surface preparation, the BCS limit can be achieved up to the critical field limit.

Nevertheless, these "imperfect" resonators can be utilized to accumulate very significant amounts of microwave energy. For example, as curve A in Figure 1 indicates, this resonator can accumulate $\simeq$ 6 J from a 180 watt S-band source. By contrast a similar room temperature copper resonator would accumulate only $\simeq 10^{-4}$ J from the same source. The surface

magnetic field at 6 J is $\simeq$ 400 gauss; since the critical field is $\simeq$ 800 gauss this superconducting resonator could accumulate up to $\simeq$ 25 J from a larger source.

PLASMA SWITCH AND PROTOTYPE AMPLIFIER

A high power plasma discharge superconducting interference switch was fabricated for this S-band TE_{022} resonator. This switch utilized a sapphire discharge tube to confine the plasma and was coupled to the resonator via an H-plane wave guide T to form a prototype amplifier. Details of the principle of such amplifiers can be found in our Jan. 1978 Report or in References 1 and 2. Curve B in Figure 1 indicates the stored energy vs. power for this device. Dielectric loss in the sapphire dominated the Q as indicated and maximum energy storage in this prototype amplifier was reduced to $\simeq$ 0.5 J from the 180 watt source.

Power gain G of the amplifier is equal to the ratio of resonator decay time ($\tau_d = Q/\omega$) to pulse length τ_p or $G = Q/\omega\tau_p$. The pulse length was chosen $\simeq$ $1/2\mu$ sec although either longer or shorter pulses can be produced easily. Consequently, a power gain of $\simeq 10^4$ was anticipated - limited in this case by dielectric loss in the switch. Pulse power gain of $\simeq 10^4$ was indeed achieved and demonstrated up to a pulse power output of 750 Kw. At $\simeq$ 750 Kw the output power was limited by breakdown in the output coaxial line and was not due to any intrinsic limit of the amplifier or technique. The 750 Kw pulses were developed by a source power of 75 watts. At this power the stored energy was $\simeq$ 0.4 J and the surface field $\simeq$ 100 gauss - far below the intrinsic capability (20-25 J) of the resonator as noted above. This small Pb superconducting S-band device, if not limited by dielectric switch loss or output breakdown, should have a power gain $\simeq 10^5$

up to the breakdown field, and develop $\simeq$ 50 MW, 1/2μsec pulses.

In summary, this demonstration was ultimately limited in power by breakdown in the output coaxial line and not a fundamental deficienty in the technique. The gain ($\times 10^4$) was limited by dielectric loss in the switch and in the absence of this loss would be $\simeq \times 10^5$ even with this "imperfect" resonator. And the theoretical (BCS) limit to gain for this prototype is $\sim 5 \times 10^5$.

Performance of the amplifier itself could thus be improved by reducing the dielectric loss in the switch element. After several experiments which verified that the losses were indeed dielectric losses in the switch tube it was decided to redesign the switch so as to remove the discharge tube and replace it by an electron (e) beam. This new switch is described in the next section. An X-band cryogenic e-beam switch has been developed and tested, and an S-band room temperature switch has also been developed and tested. However, because of time and funding limits of this Contract, we were constrained from construction and test of an S-band, cryogenic e-beam switch. Nevertheless, we are confident that an S-band cryogenic e-beam switch can be developed as a resonator switch which will not limit amplifier gain.

ELECTRON BEAM SWITCH

In order to resolve the problems of dielectric loss in the switch element, which limits the gain as just discussed, an electron beam-vacuum arc interference switch has been developed. This switch is described in an RAI Patent Disclosure #75-C-3 submitted to ONR on June 16, 1978. The principle of operation of this switch is similar to the plasma switch described in Appl. Phys. Lett. 32, 68 (1978), except that the plasma discharge tube is replaced by a vacuum arc or plasma, stimulated by an electron beam.

The electron beam is generated from a field emission cathode outside the wave guide and is introduced into the wave guide through a foil section in the top wall of the wave guide. The electron energy is adjusted so as to be large enough to allow penetration of both the foil and the medium contained within the wave guide. The experimental development carried out at X-band and S-band yielded devices with low insertion loss, high isolation, and switching rise times of order 1 nsec. The switches have been used for the purpose of releasing stored microwave energy in a variety of environments and have been shown to function in evacuated superconducting wave guides as well as room temperature guides with several atmospheres of SF_6. The switch isolation is of order 50 dB at room temperature and has surpassed 120 dB at 2°K when plated with superconducting Pb. The insertion loss is a function of the media contained within the wave guide and has varied from 0.5 dB in an evacuated X-band wave guide to 3 dB in an SF_6 pressurized S-band guide.

A schematic diagram of the electron beam generator is shown in Figure 1. A five stage Marx generator resonantly charges a 60 cm length of blumlein triax to 450 kV. The breakdown of the SF_6 switch delivers a 300 kV pulse to the 50 ohm foil diode generating an 8 K amp beam of electrons which penetrates the foil, traverses the waveguide at relativistic velocities and impacts on the far wall. The beam reaches full intensity in approximately 1 nsec and has a duration of 5 nsec, but if the waveguide contains a sufficient density of gas, the plasma produced by the ionizing

beam of electrons will continue to screen the microwave radiation until it recombines.

The voltage needed is determined by the electron penetration requirements. The electron must possess sufficient energy to penetrate the titanium foil and the gas in the waveguide. The gas enclosed within the wave guide imposes more stringent requirements on electron energy than does the titanium foil. Blooming of the electron beam over distance in the gas, while not a serious problem over the relatively small wave guide dimensions of X-band or higher frequencies, has limited the S-band switch performance. As discussed below, higher voltages would improve the S-band performance of the switch.

Using the e-beam switch, we have carried out three experiments in which energy has been stored in a microwave resonator and released. The microwave resonator is driven by a low power source for a period determined by its decay time τ_{store} and produces an output pulse upon switch closure at a power level given by

$$P_{out} = P_{in} \cdot \frac{\tau_{store}}{\tau_{release}} \cdot f \qquad (1)$$

Here f is the fraction of power transmitted to the load, and $\tau_{release}$ is the time in which the energy is transferred from the cavity after the switch has closed.

A power gain (P_{out}/P_{in}) of $3 \cdot 10^4$ was achieved at X-band with an output pulse 15 sec in duration. The energy was stored in a superconducting cylindrical resonator operating in the TE_{011} mode with $Q_L = 3 \cdot 10^7$ corresponding to a storage time τ_{store} of 0.5 msec. The cavity was strongly coupled to a superconducting electron beam

switch also located within the cryogenic enclosure. The Marx generator was used to feed a glass insulated pulse shaping line extending from the cryogenic switch through the cryogenic enclosure to the room temperature Marx generator. In this experiment the fraction of power transmitted to the load was greater than 90%.

The second and third experiments which employed room temperature S-band resonators were designed to explore the possibilities of room temperature microwave energy compression. These resonators were pressurized with SF_6 in order to explore their potential high power applications.

The first S-band resonator tested, consisted of a 150 cm section of waveguide terminated with the switch at one end and a short at the other end. This 3 GHz resonator operated with a storage time of 250 nsec and a release time of 12 nsec. The measured power gain of 12 x indicated a 3 dB insertion loss. A scope camera photograph of the diode response to the output pulse is shown in Figure 2. The approximately rectangular envelope is in agreement with the behavior one would expect based on the theory discussed below.

Finally, in a third experiment the waveguide resonator was shortened to 30 cm. The 2.5 nsec output pulse is shown in Figure 3. Here the nonrectangular nature of the pulse is believed to result from the diode response which has become more visible on this shorter time scale. The output peak pulse power of 50 times the input level indicated the same 3 dB insertion loss discussed in the previous experiment.

As previously discussed,[1-3] the switching process basically consists of shifting a reflecting plane by a quarter guide wavelength. In the absence of the electron beam, the tuned short is adjusted so that it reflects the microwaves canceling the field a half-wavelength away at the output. When the electron beam is fired it ideally creates a short one-quarter wavelength from the output which couples the microwaves directly to the matched load. If the microwave energy is stored in a cavity attached to the switching section, an exponentially decaying pulse is emitted with a release time determined by the cavity-switch coupling. If the microwave energy is stored in a section of waveguide which forms one arm of the switch, it acts as a charged transmission line which is suddenly terminated in a matched impedance and emits a pulse of microwaves with a rectangular envelope.[4] The time length of the pulse is essentially twice the length of the storage arm divided by the group velocity of the guide.

Now, in practice, the plasma will have both a finite penetration depth as well as loss due to electron lifetime effects. In order to take these into account we consider the model of the switching region shown in Figure 4. Here the output guide of the H-plane tee is represented by the matched guide impedance Z_o at section 3 and the short a distance $\lambda_g/2$ away is shown at 0. When the electron beam fires we will approximate the resulting plasma by a uniform plasma in the region $\Delta \ell$ between 1 and 2. This plasma will be characterized by an electron density n and an electron lifetime ν^{-1}.

The effective dielectric constant in this region is

$$\epsilon = \epsilon_o\left(1 - \frac{\omega_p^2}{\omega(\omega + i\nu)}\right) \qquad (2)$$

with $\omega_p^2 = ne^2/m\epsilon_o$. The resulting propagation wave vector for the TE_{10} mode in this section is

$$k^2 = \epsilon\mu_o\omega^2 - \left(\frac{\pi}{a}\right)^2 \tag{3}$$

where a is the wave guide width. For the plasma densities of interest, the real part of ϵ is negative so that it is useful to let $k = i\gamma$. Substituting the expression given by Eq. (2) for ϵ into Eq. (3) we have

$$\gamma^2 = k_o^2\left[\frac{\omega_p^2}{\omega^2 + \nu^2} + \left(\frac{k_c}{k_o}\right)^2 - 1 + \frac{j\omega_p^2\nu}{\omega(\omega^2 + \nu^2)}\right] \tag{4}$$

Here k is the free space wave vector $\sqrt{\epsilon_o\mu_o}\,\omega$, and k_c is the cutoff wave vector π/a.

The wave impedance in the plasma region of the guide is given by

$$Z = \omega\mu_o/k = -\,i\,Z_o k_g/\gamma \tag{5}$$

Here Z^o and k_g are the wave impedance and guide wave vector respectively of the TE_{10} mode at frequency ω in the absence of the plasma.

$$Z = \omega\mu_o/k_g \quad , \quad k_g^2 = k_o^2 - k_c^2 \tag{6}$$

We can now proceed to find the impedance at position 3 of Figure 4 when the plasma is fired. For $\Delta\ell$ small compared to a guide wavelength, the short at 0 appears to a good approximation as an open at 1. Then moving across the plasma section from 1 to 2 an open at 1 transforms at 2 to an impedance Z(2) given by

$$Z(2) = \frac{Z}{\tanh\gamma\Delta\ell} \tag{7}$$

Here γ is determined from Eq. (4) and Z from Eq. (5). Finally, going approximately another quarter wavelength to 3 we find

$$\frac{Z(3)}{Z_o} \simeq \frac{Z_o}{Z(2)} \tag{8}$$

The wave stored to the left of position 3 sees Z(3) in parallel with the matched output guide impedance Z_o giving an effective impedance $Z_o Z(3)/\left(Z_o + Z(3)\right)$. Thus the reflection coefficient at 3 for waves incident from the left after the electron beam has fired is given by

$$\Gamma = \frac{-1}{1 + 2Z(3)/Z_o} = \left(1 + \frac{2Z_o}{Z} \tanh \gamma \Delta \ell\right)^{-1} \tag{9}$$

and the fraction of power transferred into the output guide represented by Z_o is

$$f = \left(1 - |\Gamma|^2\right) \mathrm{Re}\left(\frac{Z(3)}{Z_p + Z(3)}\right) \tag{10}$$

Here the first factor is the transmission and the last is the ratio of the power transmitted down the output guide to the sum of this power plus the power dissipated in the plasma.

Taking ν^{-1} equal to the transit time of electrons across the guide we have calculated the fraction of the power reflected $|\Gamma|^2$ at the output guide, position 3 of Figure 4, and the fraction f of the power transmitted to the load Z_o. For the S-band case in which $\nu^{-1} \simeq 2 \times 10^{-10}$ sec and $\omega \sim 3 \times 10^9$, these are plotted versus the electron density n in Figure 5. These two figures clearly show the two effects of a non-ideal reflecting region previously discussed.

As n decreases, an increasing fraction of the power is reflected rather than transmitted to the output guide. In addition, because of the electron loss the plasma can absorb energy decreasing the amount switched to the load. As n increases and the penetration depth decreases both of these effects are reduced. In the X-band experiments it was possible to achieve densities of order 10^{12} e/cm^3, giving excellent switching action. However, the S-band experiments involved propagating the beam over larger distances, and due to blooming the average plasma densities dropped to approximately 2×10^{11} e/cm^3. At this density a little over 10% is reflected, and almost half of the remaining power is absorbed in the plasma giving rise to an insertion loss of order 3 dB.

We believe that there are some significant advantages in using an electron beam to drive the switch. First, nothing needs to be placed inside the wave guide. In some of our previous experiments[1,2] a tube was used to hold He gas which was then discharged to form a plasma, and the dominant loss in the storage mode turned out to be associated with this tube. Second, the rise time of the electron beam is of order one nanosecond so that extremely rapid switching can be obtained. This has in fact been used to obtain significant energy compression at room temperature. Furthermore, at room temperature we were able to use the electron beam to switch when the system was filled with several atmospheres of SF_6. At this pressure of SF_6 the guide is capable of storing large field strengths. Thus the electron beam switch offers the potential for the generation of short high power microwave pulses which are not limited by critical superconducting fields or air breakdown.

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1. D. L. Birx, G. J. Dick, W. A. Little, J. E. Mercereau, and D. J. Scalapino, Appl. Phys. Lett. 32, 68 (1978).

2. D. L. Birx, G. J. Dick, W. A. Little, J. E. Mercereau, and D. J. Scalapino, Appl. Phys. Lett. 33, 466 (1978).

3. D. L. Birx and D. J. Scalapino, IEEE Trans. Mag., Mag-15, 33 (1979).

4. Since this work was carried out we have found that D. B. Schwarzkopf discussed pulse generation by switching a room temperature traveling wave resonator by means of the microwave breakdown of a gas discharge, Microwave J. 5, 172 (1962); and that H. Farber, M. Klinger, M. Sucher, and E. Malloy used a spark gap switch in a similar experiment, IEEE MTT 13, 28 (1965).

FIGURE CAPTIONS

Figure 1. S-band microwave energy, accumulated in a TE_{022} superconducting resonator, shown vs. Pump Power.

Figure 2. Schematic of the electron beam gun used to switch the H-plane T.

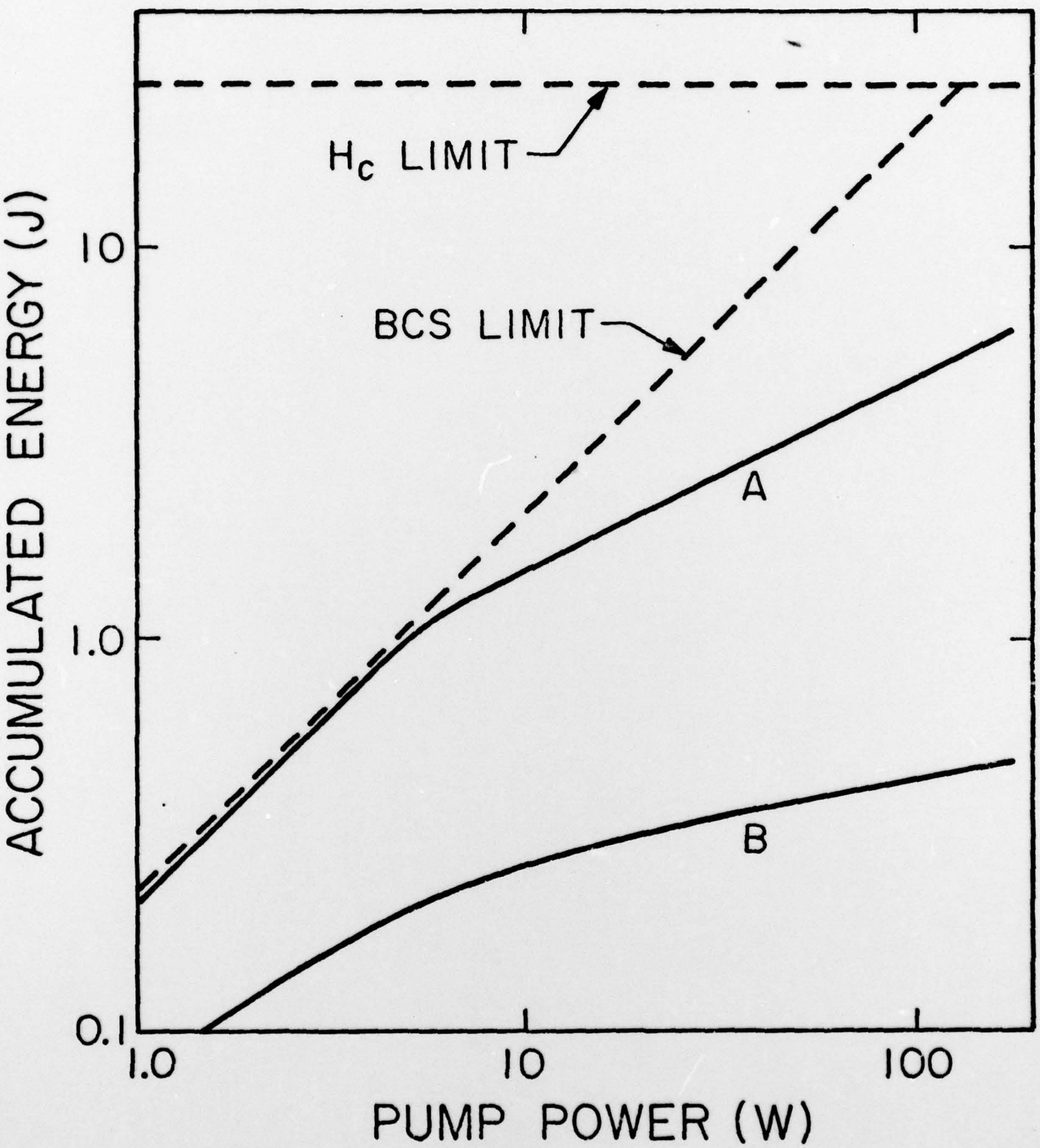
Figure 3. Output pulse from the 150 cm section of S-band guide.

Figure 4. Output pulse from a 30 cm section of S-band guide.

Figure 5. Transmission line model of the switching region.

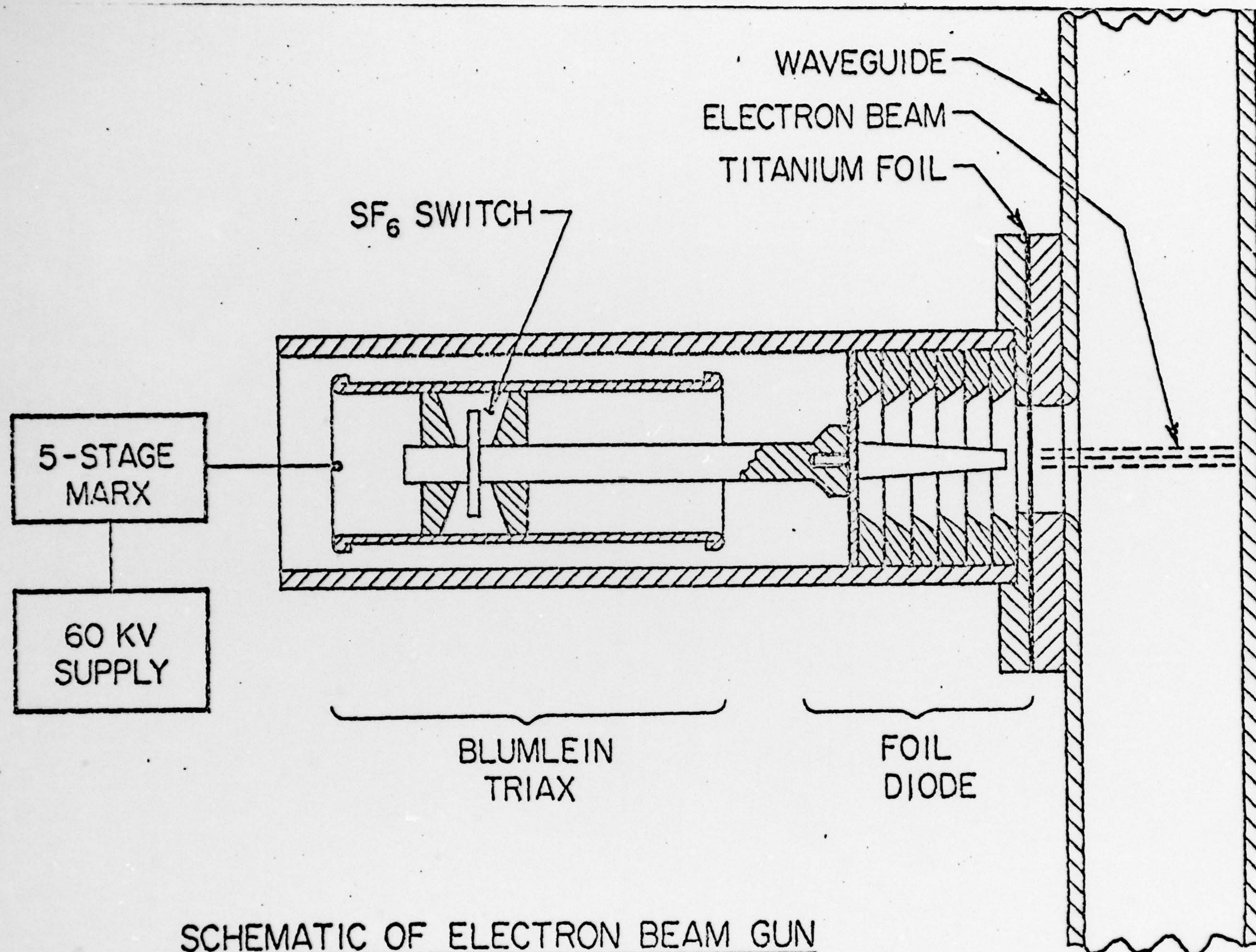
Figure 6. (a) Fraction of power reflected from the plasma, $|\Gamma|^2$, versus electron density n for an electron lifetime due to transit $\nu^{-1} = 2 \times 10^{-10}$ sec.

(b) The fraction of the power transmitted to the load versus n for $\nu^{-1} = 2 \times 10^{-10}$ sec.



H_c LIMIT
BCS LIMIT
A
B
ACCUMULATED ENERGY (J)
10
1.0
0.1
1.0
10
100
PUMP POWER (W)

FIG. 1



SCHEMATIC OF ELECTRON BEAM GUN

FIG. 2

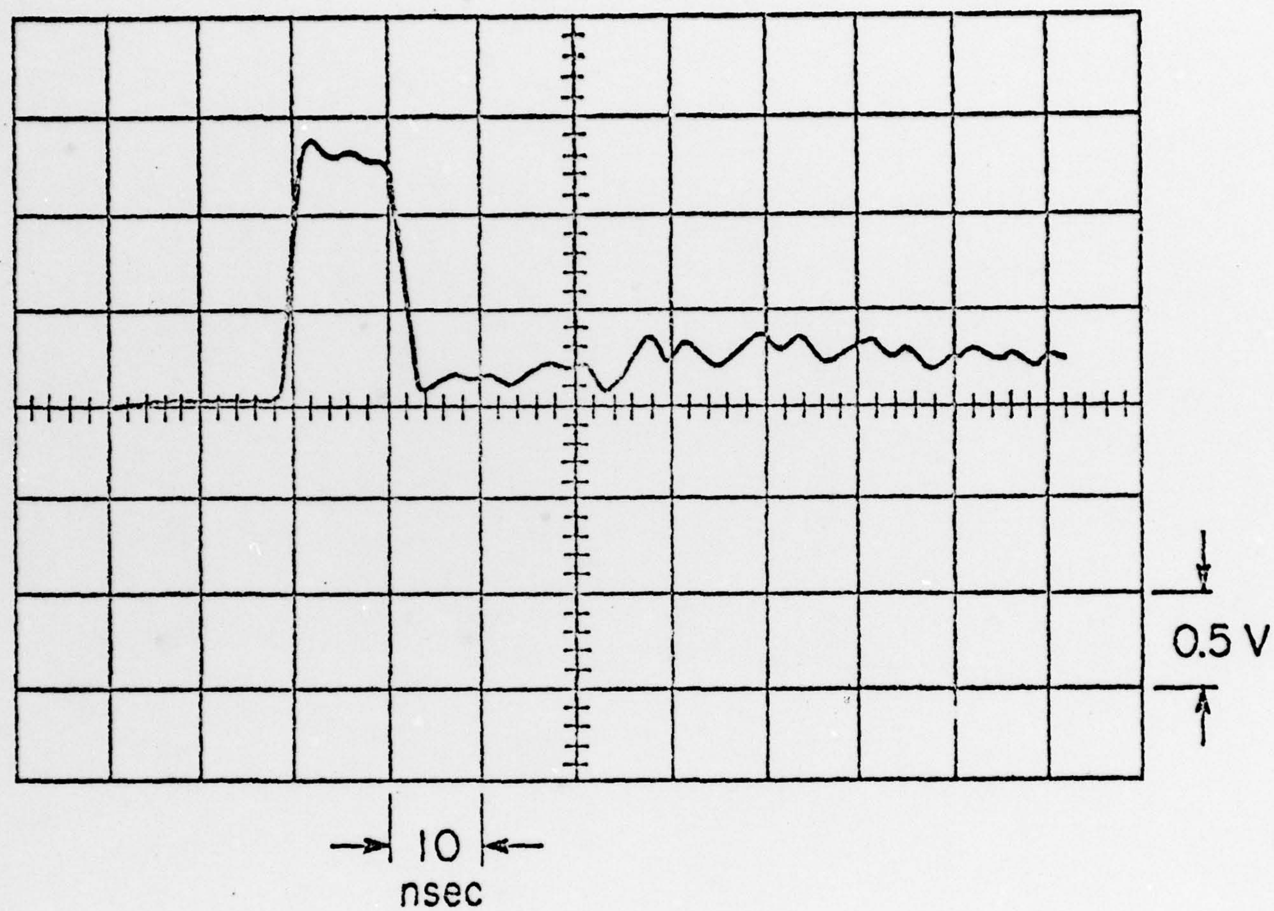


FIG. 3

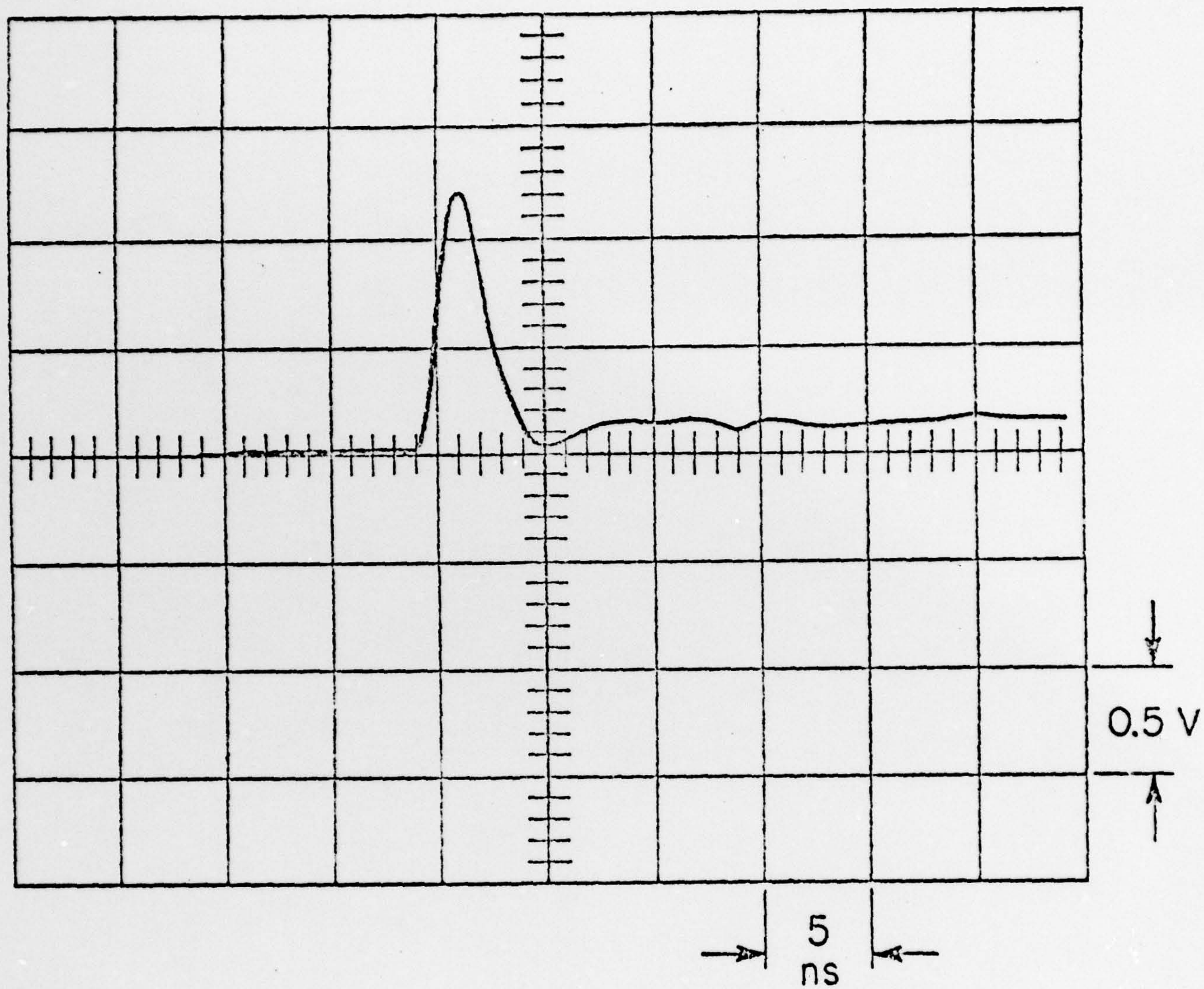


FIG. 4

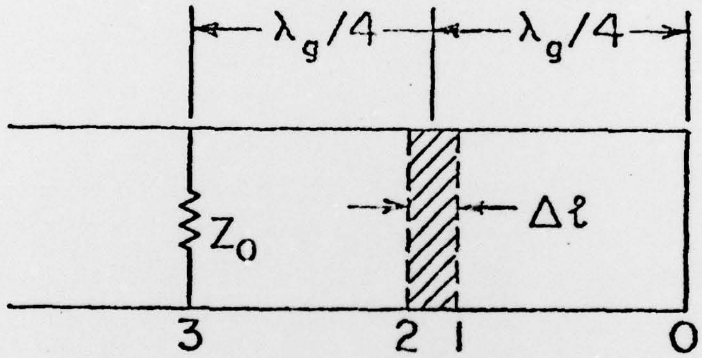


FIG. 5

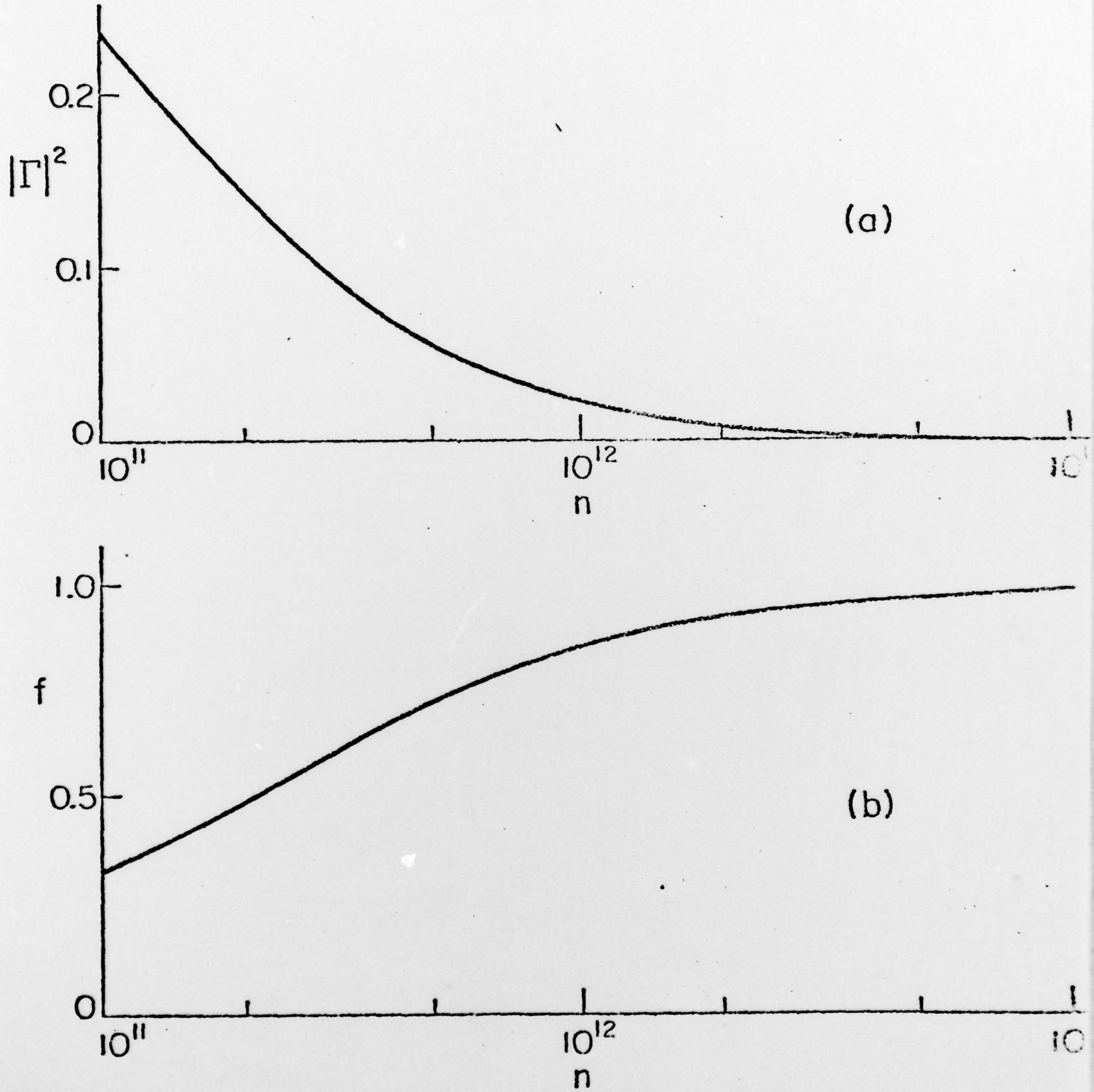


FIG. 6